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On the cosmic ray response to coronal high-speed solar wind streams

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Abstract : The influence of the regular high-speed solar wind streams (RHSSs) associated with the coronal holes on cosmic ray intensity, geomagnetic (A_p and K_p) and interplanetary parameters, has been studied for the period 1965–74. The streams considered in the span of the analysis, have been grouped into three classes (S-Short, M-Medium and L-Long) according to their time duration. Our results indicate that the combined effect of solar wind velocity (V) and interplanetary magnetic field (B) is necessary to reproduce the complete cosmic ray and geomagnetic perturbations.

Keywords : Solar wind, cosmic ray response, geomagnetic activity

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1. Introduction

It is well known that temporal variations in the solar wind features at the Earth's location (1 AU) exert a strong influence on the heliosphere, galactic cosmic rays and terrestrial magnetosphere. During the last few years, new measurements of the interplanetary medium and the sun have produced exciting and important changes in our knowledge of interplanetary phenomena. One of the most important of these phenomena of the solar-terrestrial physics, we believe, are the occurrent streams in the solar wind near the Earth. Streams are quasi-stationary, hot, low density flows, originating in coronal holes on the sun.

The satellite data collected for more than two solar-cycles have shown that high and low-speed streams are continuously reaching the Earth and they have different origins. Two types of high-speed solar wind streams have been identified [1] : (a) regular and recurrent streams coming from coronal holes (RHSSs), (b) complex and transient streams associated with solar flares (CHSSs). The origin of the low-speed solar wind streams is still an open problem. The passage towards the Earth of these high-speed solar wind streams in general, leads to geomagnetic disturbances and change in the level of cosmic ray intensity. These high-speed streams are thus a key-link in the complex chain of events that link geomagnetic activity/cosmic ray intensity to solar activity and are, therefore, of great interest to solar-terrestrial physics community [2–4].

The study of the relationship between the cosmic ray intensity variations and the interplanetary plasma parameters has been a common topic of investigation since the beginning of the space-era. Theoretical work on the physical meaning of functional relationship between cosmic ray intensity variations and interplanetary parameters is however, not in much progress and no good model has been developed so far to explain the energy transfer from solar wind to the magnetosphere [5].

Now it seems possible to forecast the geomagnetic activity and galactic cosmic ray intensity levels by means of interplanetary data, in near future [6,7]. But still a good understanding among cosmic rays, solar and geomagnetic parameters is required. Relationship between cosmic ray intensity variations, solar, interplanetary and geomagnetic parameters, has been investigated in detail but still there is a controversy on the precise role played by the solar wind speed (V) and interplanetary magnetic field (B) in influencing the cosmic ray intensity and geomagnetic indices. A detailed knowledge of the geomagnetic and cosmic ray response to each interplanetary plasma macrostructures during individual solar activity cycles is necessary to understand the long-term modulation of cosmic ray intensity in the heliosphere.

In a recent study, the cosmic ray decrease of magnitude by 1%, which resembles a co-rotating type of decrease is noted [8] The various speculations are existing about the effect involved in producing decrease in cosmic ray intensity by co-rotating streams produced by solar coronal holes [9,10].

The aim of this paper is to examine the cosmic ray and geomagnetic efficiency of interplanetary plasma macrostructures. RHSSs are co-rotating quasi-stationary structures with solar wind velocity ranging ~ 300 to 900 km/sec. In each stream, their well defined time interval may be identified at 1 AU. We have considered RHSSs, which seems to be the most appropriate plasma structures to see the influence of the solar wind parameters on cosmic rays and geomagnetic indices [11].

2. Data analysis

Sixty high-speed solar wind streams coming from coronal holes are studied, grouping them into three classes according to their time duration. For short-streams, time interval is $\Delta t \leq 4$ days (23 S-events); for medium-streams, $4 \leq \Delta t \leq 6$ days (24 M-events); and for long-streams, $6 \leq \Delta t \leq 10$ days (13 L-events) are considered.

The detailed study of the effects of three types of solar wind streams (S, M and L) on cosmic rays, observed by neutron monitor, has been done for the period 1964–74. In the analysis, the pressure-corrected cosmic ray intensity data recorded by monitor at Deep-

River (Cut of rigidity $RC = 1.02$ GV) has been used. Superposed epoch analysis of cosmic ray intensity, geomagnetic indices and interplanetary parameters have been performed. In this analysis, the arrival day (on Earth) of the streams has been taken as the epoch (zero) day. The epoch for the S-events ranging between –3 and +5 days, for M-events between –3 and +7 days and for the L-events between –3 and +9 days. The average interplanetary data at the Earth's orbit are derived from the ref. [12].

3. Results and discussion

The average time profiles (or behaviours) obtained is shown in Figure 1. Figure 1 indicates that during all classes of regular high-speed solar wind streams (short, medium and long), the cosmic ray intensity shows a decreasing tendency from a day earlier to the arrival of streams (Figure 1) at the Earth. The cosmic ray intensity decrease is very sharp during the S-streams (Figure 1a), it starts at –1 day and reaches to maximum value on +1 day and then recovery starts within two well defined steps. In first step from +1 to +2 day the recovery is very fast while it is slightly slow from +2 to +4 day. The time profile during decrease and recovery phases is quite symmetrical.

During M- and L-streams, the time profile of decrease of cosmic ray intensity seems to be similar to Forbush decrease type (Figure 1a′ and a″). The decrease phase starts

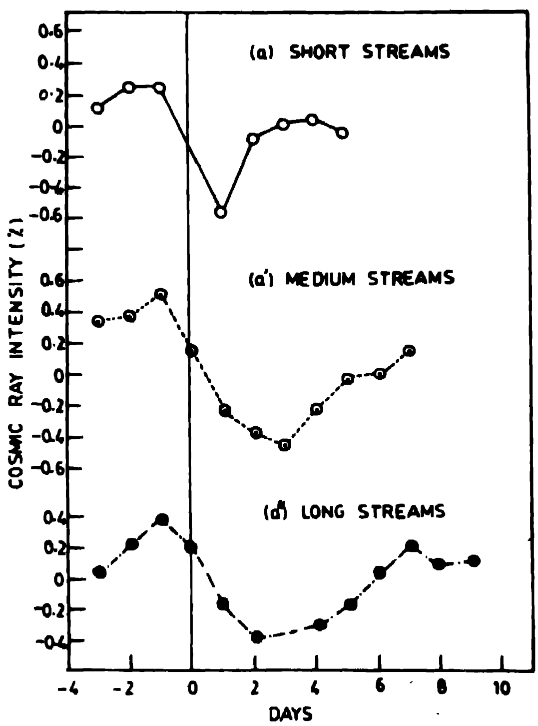

Figure 1. Superposed epoch results of cosmic ray intensity (in percent) for RHSSs divided according to their time duration (short, medium and long streams) The epoch day corresponds to the arrival day of the stream at Earth.

from −1 day as stated earlier and reaches to maximum on +3 day for M-streams and on +2 day for L-streams. Both during decrease and recovery phase, decrease and recovery of cosmic ray intensity is gradual/slow as compared to S-streams.

Figure 1 also indicates that the influence of M- and L-streams remains for a longer duration on cosmic ray intensity while the duration of the influence on cosmic ray intensity for S-streams is the shortest compared to M- and L-streams. Ananth *et al* [8] observed the magnitude of cosmic ray intensity decrease ~ 1% which might be associated with the co-rotating high-speed solar wind streams coming from coronal holes. Our results (see Table 1) corroborates the findings of earlier investigators [8,13,14].

Table 1. Average features of cosmic ray (CR) intensity during different types of streams

Class of streams	Time duration	Time of decrease	Time of recovery phase	Total time	Maximum decrease in CR intensity (%) ($-\Delta I$)	Nature of the time profile
S-stream	< 4 days	2 days	3 days	5 days	− 85 %	symmetric sharp
M-stream	$4 < \Delta t < 6$ days	4 days	4 days	8 days	−0 9 %	gradual
L-stream	$6 < \Delta t < 10$ days	3 days	5 days	8 days	-0 8 %	gradual

Average time profiles of $< CR >$, $< A_p >$, $< K_p >$, $< V >$, $< B >$, $< N_p >$ and $< T_p >$ during RHSSs is shown in Figure 2. Figure 2 indicates that for geomagnetic parameters and also for other parameters except $< V >$, $< N_p >$ and $< CR >$ the maximum are reached on the zero days, which shows that maximum energy transfer between the solar wind and the magnetosphere is associated with the transit of the co-rotating interaction region. This result is also confirmed by Akasofu [15]. Variation of cosmic ray intensity shows anti-correlation with geomagnetic indices as well as with all other parameters of the solar streams (Figure 2) with a time lag of + 1, + 2 and + 3 days between maximum of $<B>$ and $<-\Delta I>$ (maximum of cosmic ray intensity decrease) for S-, L- and M-streams. Such an anti-correlation was also reported by Duggal *et al* [16]. The maximum of solar wind velocity $<V>$ and $<-\Delta I>$ follows the zero, one or two days later and there is no time lag between two maximum $<V>$ and $<-\Delta I>$ for all classes of streams (see Table 2).

Figure 2 also indicates that the peak of cosmic ray intensity decrease $< -\Delta I >$ and the time profile of the decreasing phase occurs during a rising speed phase ($\frac{dv}{dt} > 0$), generally less than 3 days and containing the interaction region between the fast solar wind ejected by coronal hole and the slow one emitted by the solar regions located immediately west of the hole. In this interaction region, the plasma is compressed and the strength of the magnetic field is high which produces the decrease in cosmic ray intensity; similar results are also shown by the geomagnetic parameters [17,18]. The recovery of cosmic ray intensity begins during the declining speed phase ($\frac{dv}{dt} < 0$), lasting from 1 to 5 days, but

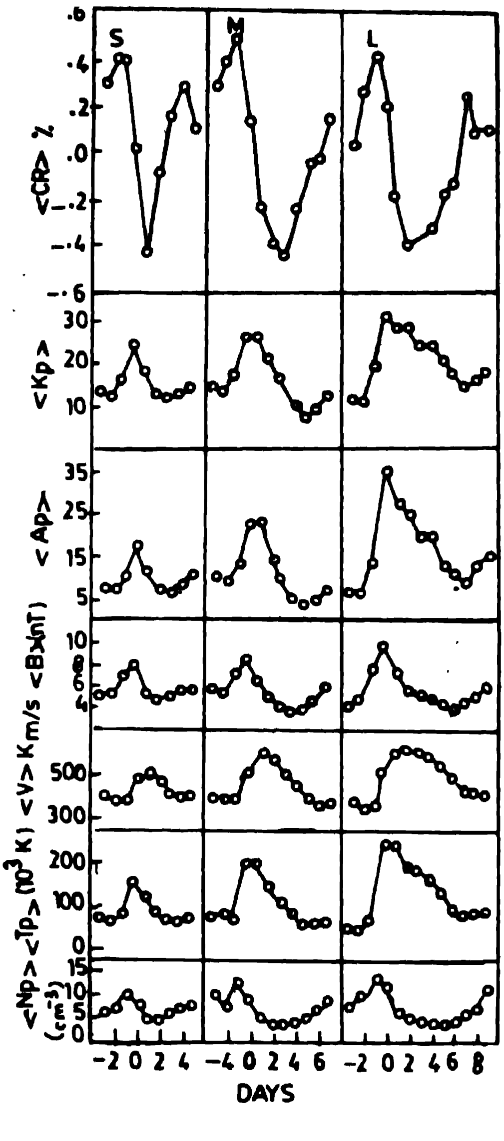

Figure 2. Superposed epoch results of < *CR* >, < *Ap* >, < *Kp* >, < *V* >, < *B* >, < *Np* > and < *Tp* > during RHSSs. The epoch day corresponds to the arrival day of the stream at Earth.

the cosmic ray recovery takes about 3 to 5 days (see Table 1). Thus, our observational results indicate that RHSSs seems to be the most appropriate plasma structures to evaluate the contribution of solar wind velocity to the cosmic ray intensity and the geomagnetic perturbations.

Temporal behaviour of cosmic ray intensity and geomagnetic parameters are very regular and similar from one stream class to another (Figure 2), a little increase in the variability in the behaviour of both is seen during longer streams. It is also clear from Figures 1 and 2 that highly disturbed days influence more strongly $< A_p >$ than $< K_p >$ and influence cosmic ray intensity for a longer duration.

Table 2. A time lag between the decrease in cosmic ray (C R) intensity, geomagnetic parameters (A_p and k_p) and interplanetary parameters (V and B).

Type of stream	ΔT_{CB}	ΔT_{CV}	$\Delta T_{ApB} / \Delta T_{kpB}$	$\Delta T_{Apv} / \Delta T_{kpv}$
S-stream	+ 1 day	0 day	0	+ 1
M-stream	+ 3 day	0 day (not well defined)	0 (not well defined)	(1–2) days
L-stream	+ days	0 day (not well defined)	0	(1–3) days

ΔT_{CB} = Time lag between C R intensity ($-\Delta I$) and magnetic field (B).
ΔT_{CV} = Time lag between C R intensity ($-\Delta I$) and solar wind velocity (V).

4. Conclusions

The study of the cosmic ray intensity and geomagnetic variations by looking the influence of interplanetary macrostructures overtaking the Earth, allows a better understanding of the cause of cosmic ray decreases and effect of solar wind parameters on cosmic ray intensity We have studied sixty high-speed streams coming from coronal holes (RHSSs) during the period 1964–74.

Our results show that the streams (RHSSs) produce a significant decrease (Forbush type) in cosmic ray intensity and significant increase in the geomagnetic indices. The cosmic ray intensity decrease begins on the day the plasma speed starts to increase and ends with the complete stream passage. The largest decreases of cosmic ray intensity are associated with the plasma rising-speed phase, which are also characterized by enhanced plasma interplanetary magnetic field strength (and plasma pressure) as expected from the co-rotating interaction passage. This sort of behaviour is found for all the three classes of streams (S, M and L). Barouch and Burlaga [19] suggested that the drifts associated with the gradient in magnetic field (B) might be a factor in producing cosmic ray intensity decreases (Forbush decreases).

Our results show that a combined effect of two important interplanetary parameters *viz.* solar wind speed (V) and interplanetary magnetic field (B) is necessary to reproduce the cosmic ray intensity behaviour during RHSSs. Similar study should be performed for CHSSs (complex and energetic solar flares) and LSSs (low-speed solar wind streams) to see the effect of interplanetary magnetic field (B) and solar wind speed (V) on the cosmic ray intensity.

It is observed that when the Earth is inside interplanetary perturbations of short duration (during S-streams), the reduction of cosmic ray intensity during the decrease and recovery phases is very fast and nearly symmetrical as compared to the long-duration perturbations (M- and L-streams), where cosmic ray intensity reduction during the decrease and recovery is slow [20,21]. Our results provide an evidence that the speed and magnetic field strength and also the presence of small-scale fluctuations (or degree or turbulences) in the magnetic field direction (not studied in this paper) may be involved in such Forbush decreases.

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